

Radioactive Properties, Internal Distribution, and Risk Coefficients

The fact sheets for the individual radionuclides contain summary-level information on the radioactive properties of the major isotopes of concern at Department of Energy (DOE) environmental management sites such as Hanford, as well as information on the potential health risks associated with exposure to these radionuclides. This information was developed using standard references and publications as identified in Table 3. The fact sheets are intentionally brief and it is not possible to include all relevant information associated with the highlights summarized in these sheets. This companion fact sheet has been prepared to provide additional context to assist the reader in understanding the basis of the information presented in the individual fact sheets and to allow for proper interpretation of the radionuclide-specific data.

Radioactive Properties. Each radionuclide fact sheet contains a table that summarizes the key properties of the various radioactive isotopes of that element. The information provided in that table includes the radioactive half-life, specific activity, radioactive decay modes, and the average energy of the emitted radiations. To simplify the presentation, all values have been rounded to two significant figures. Much of the information was obtained from Appendix G of Federal Guidance Report (FGR) Number 13 of the Environmental Protection Agency (EPA), *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*, 402-R-99-001 (September 1999). These data were also checked with the more detailed decay information in International Commission on Radiological Protection (ICRP) Report 38, *Radionuclide Transformations, Energy and Intensity of Emissions* (1983). The ICRP report is a major source of the information given in Appendix G of FGR Number 13.

Half-Life. The radioactive half-life is the length of time for a given amount of radioactive material to decrease to one half its initial amount by radioactive decay. Half-lives are constant for each radionuclide and can range from less than a second to billions of years. Only those radionuclides with half-lives longer than about one year are of concern for DOE environmental management sites, as shorter-lived radionuclides will have already decayed away to innocuous levels because production activities involving radioactive materials at major sites such as Hanford ceased more than ten years ago.

Specific Activity. The specific activity is the activity per mass and is given in units of curies (Ci) per gram in the individual fact sheets. For reference, the specific activity of radium-226 is about 1 Ci per gram, and for context 1 gram of material is about 0.035 ounce. The specific activities in the fact sheets (in units of curies per gram) were calculated using the following equation given in the Health Physics and Radiological Health Handbook (1992, p. 264). $\text{Specific Activity} = A_{\text{Ra-226}} \times T_{\text{Ra-226}} / A_i \times T_i$ where $A_{\text{Ra-226}} = 226$, the atomic number of radium-226; $T_{\text{Ra-226}} = 1,600$, the value used for the half-life of radium-226, in years (to two significant figures); A_i = the atomic number of the isotope; and T_i = half-life of the isotope in years. The specific activity can be expressed in international units by multiplying the value in the fact sheet by 3.7×10^{10} becquerels (Bq) per Ci.

Decay Mode. The radioactive decay modes identified in the fact sheets include beta-particle emission, alpha-particle emission, isomeric transition (IT), electron capture (EC), and spontaneous fission (SF). The companion fact sheet on *Ionizing Radiation* contains additional information on the first two decay modes. The IT decay mode is a process whereby a nucleus in an elevated energy state (typically a metastable isotope designated by the letter “m”) releases excess energy by emitting a gamma ray. The product of the decay is not a new isotope, but rather the same isotope in a reduced (more stable) energy configuration. The EC decay mode is a process in which an inner-shell electron orbiting the nucleus of an atom is “captured” by the nucleus where it combines with a proton to become a neutron, and excess energy is given off in the form of gamma rays. An outer-shell electron fills the “hole” left in the inner shell, and the excess energy associated with the movement of an outer-shell electron to an inner shell is given off as X-rays. The SF decay mode is a process in which an unstable nucleus splits (fissions) into two smaller products without needing additional neutrons to initiate the process, i.e., it is spontaneous. For simplicity, only the major decay modes are shown in the fact sheets; decay modes that occur less than 1% of the time are not included. Report 38 of the ICRP includes a very detailed accounting of all decay modes for each radionuclide and can be consulted for additional information.

In addition to the radioactive decay modes discussed above, there are additional mechanisms by which unstable atoms release energy. Internal conversion is a process in which the excess energy of a nucleus in an excited state is transferred to an electron orbiting the nucleus, which results in the electron being emitted from the atom. This process competes with gamma-ray emission as a mechanism for releasing excess energy from the nucleus, such as occurs during IT decay. Both internal conversion and EC result in a “hole” in the inner shell of orbital electrons, which is filled by an outer-shell electron with excess energy given off in the form of X-rays. These X-rays can interact with other orbital electrons, transferring sufficient energy to them to result in the emission of additional electrons. Such emitted electrons generated by interactions with X-rays are termed Auger electrons and have very little kinetic energy.

Decay Energy. The average energy reported for individual isotopes in the fact sheets represents the energy of the indicated radiation multiplied by the fractional yield for the given decay mode. That is, the energy reported for the various types of radiation represents the average energy per decay of the radionuclide. The energy of the radiation is given in units of million electron volts (MeV). One MeV is equal to 0.16 trillionth of a joule. The following two examples are provided to illustrate how this information should be interpreted.

Consider a radionuclide that decays by emitting an alpha particle with two different energies: half the time the energy is 5 MeV and the other half of the time the energy is 6 MeV. The energy reported for the alpha particle decay in this case would be 5.5 MeV. Consider a second example in which a radionuclide decays half the time by emitting a beta particle with an average energy of 0.5 MeV, and the other half of the time it decays by emitting an alpha particle with an energy of 6 MeV. The energy of the beta particle would be reported as 0.25 MeV (half of 0.5 MeV), and the energy of the alpha particle would be given as 3 MeV (half of 6 MeV). As a note, the average energy of a beta particle is typically about one-third the maximum energy (which is often the energy reported in radionuclide charts), or about 30% of the maximum for negatrons and 40% for positrons. (See the companion fact sheet on *Ionizing Radiation* for a discussion of negatrons and positrons.) The summary-level tables in the individual radionuclide fact sheets include the contributions of all primary (alpha and beta particles and gamma rays) and secondary (X-rays and Auger electrons) radiations.

The average energy reported for gamma rays in the fact sheets includes the contributions of X-rays and has been adjusted to account for the fractional yield. The only difference between these two types of electromagnetic radiation is their origin, and hence energy. Gamma rays originate in the nucleus as a means of releasing excess energy from the atom, while X-rays are emitted when electrons outside the nucleus move from higher to lower energy states. Radionuclides having gamma-ray energies less than 0.03 MeV per decay, considering the fractional yield (as described above), generally do not present a health concern from external gamma exposure. The average energy per decay reported for beta particles includes the contributions of all electrons and positrons regardless of their origin (internal or external to the nucleus). The average energy per decay reported for alpha particles does not include the contribution of the recoiling atom (which is typically quite small, e.g., a few percent of the total energy associated with the alpha-decay process).

Some radionuclides decay into short-lived daughters that always accompany the parent. (The term *parent* is used to describe the original isotope, and *daughter* is used for the decay product.) For example, strontium-90 decays to yttrium-90 by emitting a beta particle with a 29-year half-life. The daughter yttrium-90 quickly decays by emitting a beta particle, with a half-life of 64 hours. So for all practical purposes, each decay of strontium-90 can be considered to yield two beta particles, one for strontium-90 and one for yttrium-90. Short-lived decay products need to be considered when estimating the potential health effects of exposures to radionuclides. To facilitate this consideration, the radioactive properties of both the parent and its short-lived daughter(s) are presented in the individual radionuclide fact sheets.

Internal Distribution. To estimate the human health risks associated with radionuclides, it is necessary to follow the movement of the isotopes from intake through excretion. These isotopes constantly emit radiation at a rate proportional to their specific activity as they pass through the body irradiating various organs. Some radionuclides very quickly deposit in one or two organs; others deposit more slowly throughout the entire body. Various models and computer codes have been developed by the ICRP, EPA, and other national and international organizations to estimate internal radiation doses and risks from intake of radionuclides. These models are based on extensive animal and human data and can be quite complex. A number of codes and models were considered by the EPA in developing the risk coefficients presented in FGR Number 13, as illustrated by the references in that document. The risk coefficients were calculated using the DCAL (Dose and Risk Calculation) software developed by Oak Ridge National Laboratory for the EPA. The DCAL is a comprehensive system for calculating radiation dose and risk coefficients using age-dependent models that incorporate information developed by the ICRP and other organizations on the distribution and retention of radionuclides by various organs in the body. The primary distribution of selected radionuclides in the body is shown in Figure 1 of the accompanying distribution fact sheet.

Risk Coefficients. The EPA has developed mortality risk coefficients for nearly all radionuclides to estimate the lifetime risk of incurring a fatal cancer from environmental exposures using the DCAL software as described in FGR Number 13. These coefficients have been calculated by state-of-the-art methods and computer models that take into account age and gender dependence of intake, metabolism, dosimetry, and radiogenic risk, as well as competing causes of death, to estimate health risks from internal and external exposures. The values are given per unit uptake (picocurie, pCi) averaged over all ages and both genders. (For context, 10^{-9} is a billionth, 10^{-12} is a trillionth, and a pCi is a trillionth of a Ci.) To convert to standard international units, the given values should be multiplied by 27 pCi/Bq.

Each radionuclide fact sheet contains a table with selected mortality risk coefficients for inhalation and ingestion, which are also summarized in Table 1. These values include the contributions from short-lived decay products, as identified on the radioactive properties summary table described above (e.g., the value for strontium-90 includes the contribution from yttrium-90). For inhalation, the values correspond to the recommended default absorption type for particulates, except as otherwise noted (e.g., the tritium values are for tritiated water). For ingestion, the dietary values shown are the highest for ingestion exposures; the values for tap water ingestion vary by radionuclide and are typically 70 to 80% of those for dietary intake. Coefficients are also available to estimate the risk of incurring all types of cancer (morbidity risk coefficients), and these values also vary by radionuclide. For most radionuclides, the ingestion mortality coefficients are on the order of 60 to 80% of the morbidity values, with iodine an exception at about 10%. For inhalation the percentages are a bit higher, ranging from 70% (for cesium and tritium) to nearly 100% (for uranium-234 and uranium-238), with the mortality coefficient for iodine again much lower at about 10%. For major gamma-emitting radionuclides, risk coefficients are shown in Table 1 and risk text is included in the fact sheet.